

Monopole giant resonance in $^{100-132}\text{Sn}$, ^{144}Sm and ^{208}Pb

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The isoscalar giant monopole resonance (GMR) in spherical nuclei $^{100-132}\text{Sn}$, ^{144}Sm , and ^{208}Pb is investigated within the Skyrme random-phase-approximation (RPA) for a variety of Skyrme forces and different pairing options. The calculated GMR strength functions are directly compared to the available experimental distributions. It is shown that, in accordance to results of other groups, description of GMR in Sn and heavier Sm/Pb nuclei needs different values of the nuclear incompressibility, $K \approx 200$ or 230 MeV, respectively. Thus none from the used Skyrme forces is able to describe GMR in these nuclei simultaneously. The GMR peak energy in open-shell ^{120}Sn is found to depend on the isoscalar effective mass, which might be partly used for a solution of the above problem. Some important aspects of the problem (discrepancies of available experimental data, proper treatment of the volume and surface compression in finite nuclei, etc) are briefly discussed.

I. INTRODUCTION

During the last decades, the giant monopole resonance (GMR) was subject of intense studies, see e.g. [1–3] for recent reviews and discussions. The GMR provides a valuable information on the nuclear incompressibility [4] since its energy centroid E_{GMR} can be directly related to the compression modulus K_A within a collective model [4],

$$E_{\text{GMR}}^A = \sqrt{\frac{\hbar^2 K_A}{m \langle r^2 \rangle_0}}, \quad (1)$$

where A is the nucleus mass number, m is the nucleon mass, and $\langle r^2 \rangle_0$ is the ground-state mean-square radius. For nuclear matter, the commonly accepted value for incompressibility is $K = 230\text{--}240$ MeV, confirmed by relativistic as well as non-relativistic mean field models [5].

Despite many efforts, the description of GMR still suffers from some persisting problems. For example, the mean field models with $K = 230\text{--}240$ MeV reproduce the GMR experimental data in heavy and medium nuclei, like ^{208}Pb and ^{144}Sm [6, 7, 9], but fail to describe more recent GMR experiments for lighter nuclei, like Sn and Cd isotopes [10–14], which request a lower incompressibility (see e.g. the discussion in [1, 2, 15, 16]). In other words, none of the modern self-consistent models, relativistic or non-relativistic, can simultaneously describe the GMR in all mass regions. This problem has been already analyzed from different sides. It was shown that GMR centroids can be somewhat changed by varying the symmetry energy at constant K [17]. Different Skyrme forces and pairing options (surface, volume, and mixed) were inspected [2, 15, 16]. Hartree-Fock-Bogoliubov (HFB) and HF-BCS methods were compared [18]. All these attempts have partly conformed the description but not solved the problem completely.

The modern GMR experimental data are mainly delivered by two groups: Texas A&M University (TAMU) [6, 9, 10] and Research Center for Nuclear Physics

(RCNP) at Osaka University [7, 11–14]. Both groups use (α, α') reaction and multipole decomposition prescription to extract the E0 contribution from the cross sections. However, these groups provide noticeably different results and this should be also taken into account in the analysis of the above problem [2, 19].

The present paper is also devoted to the problem of the simultaneous description of the GMR in Sm-Pb and Sn nuclei. For this aim, the E0 strength functions are calculated within Skyrme RPA [23] and directly compared to the available experimental data. Note that in some previous studies [2, 18] the GMR analysis was limited to inspection of energy centroids calculated through sum rules. Such analysis can be ambiguous as it depends on the choice of the energy interval where the sum rules are calculated. Besides that, gross structure of E0 strength in the GMR and around (e.g. a high-energy essential tail of the E0 strength in the RCNP data [7, 11–14]) escapes considerations. In our opinion, a detailed exploration should include a direct comparison of the calculated and experimental strength distributions, which is just done in the present study.

Our calculations are performed using the family of SV Skyrme forces [20] which cover a wide range of the nuclear matter parameters and thus are convenient for a systematic investigation. Both surface and volume pairing options are applied. As shown below, our analysis confirms that incompressibility $K \approx 230$ MeV suits to describe E0 strength in heavier nuclei (^{208}Pb and ^{144}Sm) while lighter Sn isotopes need lower values $K \approx 200$ MeV. In connection to this problem, a significant discrepancy between TAMU and RCNP experimental data is discussed. Besides we inspect dependence of the GMR peak energy on various nuclear matter variables in three representative Sn isotopes: neutron-deficit doubly magic ^{100}Sn , stable semi-magic ^{120}Sn , and neutron-rich doubly magic ^{132}Sn .

The paper is organized as follows. In Sec. II, the theoretical framework and calculation details are sketched. In Sec. III, the results are discussed. Further the summary is done.

II. THEORETICAL FRAMEWORK

The calculations of the E0 strength function are performed within RPA based on the Skyrme energy functional (see e.g. [20])

$$\mathcal{E}(\rho, \tau, \vec{J}, \vec{j}, \vec{\sigma}, \vec{T}) = \mathcal{E}_{\text{kin}} + \mathcal{E}_{\text{Sk}} + \mathcal{E}_{\text{Coul}} + \mathcal{E}_{\text{pair}} \quad (2)$$

depending on a couple of local densities ($\rho(\vec{r})$ - nucleon, $\tau(\vec{r})$ - kinetic energy, $\vec{J}(\vec{r})$ - spin-orbit, $\vec{j}(\vec{r})$ - current, $\vec{\sigma}(\vec{r})$ - spin, $\vec{T}(\vec{r})$ - vector kinetic energy). Here \mathcal{E}_{kin} , \mathcal{E}_{Sk} , $\mathcal{E}_{\text{Coul}}$ and $\mathcal{E}_{\text{pair}}$ are kinetic energy, Skyrme, Coulomb, and pairing terms, respectively. The explicit expressions for these terms are found elsewhere, see e.g. [20].

Using Hartree-Fock (HF) with BCS treatment of the pairing we obtain the effective Hamiltonian as a sum of the quasiparticle mean field $\hat{h}_{\text{HF+BCS}}$ and residual interaction \hat{V}_{res} [20–22]:

$$\hat{H} = \hat{h}_{\text{HF+BCS}} + \hat{V}_{\text{res}} \quad (3)$$

where

$$\hat{h}_{\text{HF+BCS}} = \int d^3r \sum_{d+} \frac{\delta \mathcal{E}}{\delta J_{d+}(\vec{r})} \hat{J}_{d+}(\vec{r}), \quad (4)$$

$$\hat{V}_{\text{res}} = \frac{1}{2} \sum_{d,d'} \int d^3r \int d^3r' \frac{\delta^2 \mathcal{E}}{\delta J_d \delta J_{d'}} : \hat{J}_d(\vec{r}) \hat{J}_{d'}(\vec{r}') : . \quad (5)$$

The $\hat{h}_{\text{HF+BCS}}$ involves only time-even densities (ρ, τ, \vec{J}) while in \hat{V}_{res} all the densities are embraced. The symbol $::$ in (5) means the normal product of the involved operators with respect to the quasiparticle creation α_i^+ and annihilation α_i operators [22]. Then, using the standard RPA procedure, we obtain the RPA equation

$$\begin{pmatrix} A & B \\ B^* & A^* \end{pmatrix} \begin{pmatrix} c^{(\nu-)} \\ c^{(\nu+)} \end{pmatrix} = \begin{pmatrix} E_\nu & 0 \\ 0 & -E_\nu \end{pmatrix} \begin{pmatrix} c^{(\nu-)} \\ c^{(\nu+)} \end{pmatrix} \quad (6)$$

for the two-quasiparticle (2qp) forward and backward amplitudes $c^{(\nu\pm)}$ of the phonon creation operator

$$Q_\nu^+(\lambda\mu) = \sum_{i \geq j} C_{j_i m_i j_j m_j}^{\lambda\mu} \left(c_{ij}^{(\nu-)} \alpha_i^+ \alpha_j^+ - c_{ij}^{(\nu+)} \alpha_j^- \alpha_i^- \right). \quad (7)$$

Here $C_{j_i m_i j_j m_j}^{\lambda\mu}$ are Clebsch-Gordan coefficients, ν numerates RPA states, E_ν is the RPA energy, A and B stand for the RPA matrices with the elements

$$A_{ijkl} = \delta_{ij,kl} \epsilon_{ij} + \sum_{d,d'} \frac{(-1)^{l_j+l_l}}{2\lambda+1} \int_0^\infty dr r^2 \frac{\delta^2 \mathcal{E}}{\delta J_d \delta J_{d'}} J_{d;ij}^{(\lambda)}(r) J_{d';kl}^{*(\lambda)}(r), \quad (8)$$

$$B_{ijkl} = \sum_{d,d'} \frac{\gamma_d (-1)^{l_j+l_l}}{2\lambda+1} \int_0^\infty dr r^2 \frac{\delta^2 \mathcal{E}}{\delta J_d \delta J_{d'}} J_{d;ij}^{(\lambda)}(r) J_{d';kl}^{*(\lambda)}(r) \quad (9)$$

where ϵ_{ij} are 2qp energies, $\gamma_d=+1$ for time-even and -1 for time-odd densities. Further, $J_{d;ij}^{(L)}(r)$ are radial parts of decompositions [22]

$$\hat{J}_d(\vec{r}) = \sum_{ijLM}^{i>j} J_{d;ij}^{(L)}(r) \frac{(-1)^{l_i+L+1}}{\sqrt{2\lambda+1}} C_{j_i m_i j_j m_j}^{LM} Y_{LM}(\hat{r}) \left(\alpha_i^+ \alpha_j^+ - \gamma_d \alpha_j^- \alpha_i^- \right), \quad (10)$$

where $Y_{LM}(\hat{r})$ are spherical harmonics (more complicated radial parts for the vector and tensor densities can be found in [22]). Diagonalization of the RPA matrix gives amplitudes $c_{ij}^{(\nu\pm)}$ and phonon energies E_ν .

By using the structure and energies of one-phonon states, the strength function

$$S(E0, E) = \sum_\nu \left| \langle \nu | \hat{M}(E0) | 0 \rangle \right|^2 \xi_\Delta(E - E_\nu) \quad (11)$$

for the monopole transition operator $\hat{M}(E0) = r^2 Y_{00}$ is calculated. The Lorentz weight

$$\xi_\Delta(E - E_\nu) = \frac{1}{2\pi} \frac{\Delta}{(E - E_\nu)^2 + \frac{\Delta^2}{4}} \quad (12)$$

with the averaging parameter $\Delta = 2$ MeV is used. Such averaging is found optimal for a simulation of the smoothing effects beyond RPA (escape widths and coupling to complex configurations). This then allows a convenient comparison of the calculated and experimental strengths.

The calculations exploit a set of Skyrme SV forces [20], consisting of groups of parameterizations with varying one of the nuclear matter variables: incompressibility modulus K , isoscalar effective mass m_0^*/m , TRK sum-rule enhancement κ (related to the isovector effective mass), and the symmetry energy a_{sym} . Thus SV forces are convenient for systematic investigation of the dependence of the results on the basic nuclear matter features. For the comparison, some other Skyrme parameterizations with essentially different incompressibilities are used: SkP $^\delta$ ($K = 202$ MeV) [24], SKM* ($K = 217$ MeV) [25], SLy6 ($K = 230$ MeV) [26], and SkI3 ($K = 258$ MeV) [27].

In our strength distributions, the spurious mode related to the pairing-induced non-conservation of the particle number lies at 4-6 MeV, which is safely below the GMR peaked at 14-16 MeV. To minimize the impact of the spurious mode, only the strength at the excitation energy $E > 9$ MeV is considered.

The calculations use a radial coordinate-space grid with step size 0.1 fm. The large configuration space involving 2qp spectrum up to 140 MeV is exploited. The energy weighted sum rule EWSR(E0) = $\frac{\hbar^2}{2\pi m} A \langle r^2 \rangle_0$ estimated at the energy interval 9-45 MeV is exhausted by 98-105%. The excess of EWSR arises in nuclei with pairing due to the remaining weak tail of the spurious mode.

Proton and neutron pairing are taken into account in semi-magic ^{144}Sm and $^{112,116,120,124}\text{Sn}$, respectively. The

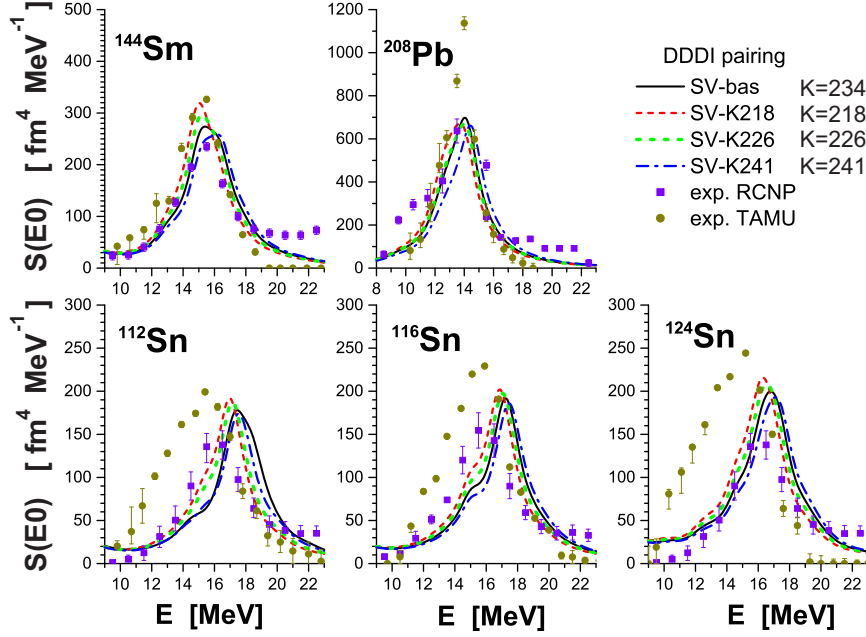


FIG. 1: $E0(T=0)$ strength functions in ^{144}Sm , ^{208}Pb and $^{112,116,124}\text{Sn}$, calculated with SV forces SV-K218, SV-K226, SV-bas, and SV-K241. The incompressibility moduli K are indicated for each force in MeV. In Sm and Sn, the DDDI pairing is used. The Lorentz averaging parameter is $\Delta = 2$ MeV. The results are compared with TAMU data for Sm/Pb [6, 9], and Sn [10] and RCNP data for Sm [7], Pb [8], and Sn [11].

pairing potential reads

$$V_{\text{pair}}(\vec{r}, \vec{r}') = V_{0,q} \left[1 - \eta \left(\frac{\rho(\vec{r})}{\rho_0} \right) \right] \delta(\vec{r} - \vec{r}'), \quad (13)$$

where q stands for protons or neutrons. The $V_{0,p}$ and $V_{0,n}$ are the pairing strengths, $\rho(\vec{r})$ is the nucleon density and ρ_0 is the density of symmetric nuclear matter at equilibrium. The parameter η switches the pairing options between the volume delta-interaction (DI) for $\eta=0$ and surface density-dependent delta-interaction (DDDI) for $\eta=1$. Both options are used in the calculations. Pairing is treated at the BCS level. This means that, at each HF iteration for single-particle wave functions, the Bogoliubov coefficients u_i and v_i are determined within the BCS and then introduced to the Skyrme densities. However here, unlike the HFB case, the HF iterations exploit the single-particle hamiltonian without the pairing term [28]. The RPA calculations take into account the pairing particle-particle channel.

III. RESULTS AND DISCUSSION

Figure 1 shows the RPA results for isoscalar ($T=0$) GMR in doubly-magic ^{208}Pb , neutron semi-magic ^{144}Sm , and proton semi-magic $^{112,116,124}\text{Sn}$. The SV parameterizations with different values of the incompressibility K (as indicated at the figure) are used. The calculated strength functions are compared with TAMU [6, 9, 10] and RCNP [7, 8, 11] experimental data. For the convenience of comparison, the TAMU data, being initially

presented in units of the fraction of the EWSR, are transformed to units $\text{fm}^4 \text{MeV}^{-1}$ used by RCNP. In the calculated strength function, the Lorentz averaging parameter $\Delta=2$ MeV is used as most convenient for the comparison between the calculated and RCNP strengths. Such averaging produces GMR amplitudes and widths similar to the RCNP ones. Then the actual model output is reduced to the GMR shape, integral strength, and energy. As seen from Fig. 1, the calculated GMR integral strength is close to the RCNP one expressed in the same units.

Before further comparison of the theory and experiment, the significant discrepancy between RCNP and TAMU data should be discussed. Fig. 1 shows a large difference at the left wing of the GMR strength. In principle, this difference can be reduced by a proper re-scaling of the TAMU data. However, scaling cannot conceal two other apparent differences. First, as compared to RCNP, TAMU gives somewhat lower energy position of the GMR peak in Sm and Sn. Second, the RCNP data exhibit a long uniform tail above the GMR. Only onset of this tail at $19 \text{ MeV} < E < 23 \text{ MeV}$ is seen in Fig. 1, though actually it continues at least up to 33 MeV [11]. Such a tail is absent in TAMU data, see discussion [9]. This difference can affect determination of the experimental GMR centroids which are usually estimated through the sum rules and thus depend on the chosen energy intervals. Altogether, these two RCNP/TAMU discrepancies should be taken into account in the comparison of the calculated GMR with the experiment.

Figure 1 also shows that, in accordance to previous

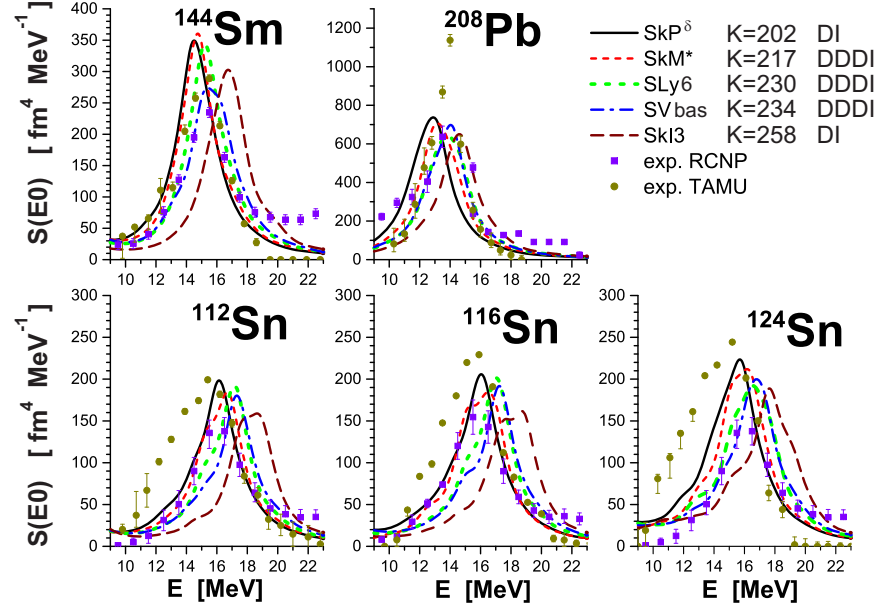


FIG. 2: The same as in Fig. 1 but for the Skyrme forces SkP^δ , SkM^* , SLy6 , SV-bas , and SkI3 . The incompressibility moduli K (in MeV) and pairing options (DI or DDDI) are indicated for each force.

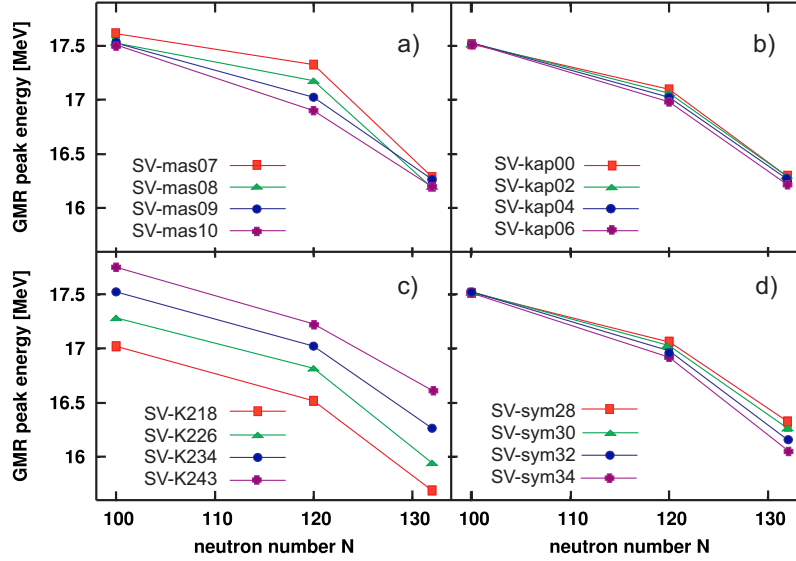


FIG. 3: Dependence of the GMR peak energies in $^{100,120,130}\text{Sn}$ on the nuclear matter values: (a) isoscalar effective mass ($m_0^*/m=0.7, 0.8, 0.9, 1.0$), b) isovector enhancement factor ($\kappa=0, 0.2, 0.4, 0.6$), c) incompressibility modulus ($K=218, 226, 234, 243$ MeV) and d) symmetry energy ($a_{\text{sym}}=28, 30, 32, 34$ MeV). The RPA calculations [23] are performed with the family of SV Skyrme forces [20].

studies (see [1, 2] and references therein), the calculate energy position of the GMR noticeably depends on the the incompressibility K . The larger K , the higher GMR. For instance, in ^{144}Sm the force SV-K241 with $K=241$ MeV gives the GMR maximum at 16.2 MeV while SV-K218 with $K=218$ MeV downshifts this maximum to 15 MeV. It is also seen that the forces with a large K , like SVbas , provide a good agreement with TAMU and RCNP data in heavy nuclei ^{144}Sm and ^{208}Pb but certainly overestimate the GMR energy in lighter Sn iso-

topes. The description of GMR in Sn needs forces with a much smaller incompressibility (even the force SV-K218 is not enough). In other words, Sn isotopes demonstrate a remarkable softness to the compression and this is valid for both RCNP and TAMU data.

These conclusions are corroborated in Fig. 2 where Skyrme parameterizations beyond the SV-family (SkP^δ [24], SkM^* [25], SLy6 [26], SkI3 [27]) with a broader incompressibility range $K=202 \div 258$ MeV are applied. Fig. 2 shows that the best description of the GMR en-

ergy E_{GMR} in Sn isotopes is obtained with the low- K SKP $^\delta$ and SkM* forces but these forces noticeably underestimate the GMR energy in ^{144}Sm and ^{208}Pb . For the latter nuclei, the parametrization SV-bas with a large $K=234$ MeV is best but it fails in Sn isotopes. The force SKI3 with the highest incompressibility $K = 258$ MeV overestimates E_{GMR} in all the considered nuclei. Both pairing options, DI and DDDI, give similar results.

It is instructive to compare sensitivity of the centroid energy E_{GMR} to K and also to other nuclear matter variables. Fig. 3 shows the dependence of E_{GMR} on the isoscalar effective mass m_0^*/m , isovector enhancement factor κ , incompressibility K , and symmetry energy a_{sym} for neutron-deficit doubly-magic ^{100}Sn , stable semi-magic ^{120}Sn , and neutron-rich doubly-magic ^{132}Sn . One finds that E_{GMR} indeed depends most strongly on K : the difference in E_{GMR} for $K=218$ and 243 MeV reaches 1 MeV. The E_{GMR} decreases from ^{100}Sn to ^{132}Sn in general agreement with the empirical estimation $E_{\text{GMR}}^e \approx 78A^{-1/3}$ MeV [29]. The dependence of E_{GMR} on κ and a_{sym} is generally weak (for exception of the neutron-rich nucleus ^{132}Sn). However ^{120}Sn demonstrates a significant dependence on the isoscalar effective mass: the less m_0^*/m , the higher E_{GMR} . This is because decrease of m_0^*/m makes the single-particle spectrum more dilute and thus results in higher E_{GMR} . In ^{120}Sn , this effect seems to be enhanced by the neutron pairing. Dependence on m_0^*/m can be used for a further conformance of the GMR description in Pb/Sm and Sn nuclei.

Finally note that the problem of the simultaneous description of the GMR in Pb/Sm and Sn can have various reasons. Perhaps available Skyrme parameterizations and pairing treatments are not yet optimal enough. It is also possible that accuracy of the Skyrme-like energy density functionals have already reached their limits (see discussion [30]) and some essential modifications of the functionals, e.g. a richer density dependence [31], are in order. Note that there are also other cases when Skyrme forces cannot simultaneously describe nuclear excitations in closed- and open-shell nuclei. For example, none Skyrme parametrization can simultaneously reproduce the spin-flip M1 GR in closed-shell spherical ^{208}Pb and open-shell rare-earth deformed nuclei [32, 33]. More versatile density dependence would also allow to distinguish between the bulk incompressibility K and surface incompressibility K_A^{sur} . Note that the incompressibility in finite nuclei can be different at the nuclear surface and interior because these regions have different nucleon densities. Besides, at the nuclear surface, the impact of pairing is most essential. So the separate consistent estimations of the volume K_A^{vol} (to be associated with the nuclear matter incompressibility K) and surface K_A^{sur} incompressibility might be useful, see analysis of the leptodermous expansion of K_A in [3].

As mentioned above, the discrepancy between RCNP

and TAMU experimental data also hampers solution of the problem. Note that RCNP/TAMU data deviate also in deformed nuclei. For example, TAMU gives (in agreement with recent Skyrme RPA calculations [19]) a clear two-bump GMR structure in ^{154}Sm [9], explained by the deformation-induced coupling between $E0(T=0)$ and $E2(T=0)$ modes. Instead RCNP data give in this nucleus a one-bump GMR structure [7]. In this connection, note that TAMU and RCNP experiments use α -particle beams with different incident energies. Since (α', α) is a peripheral reaction, the TAMU and RCNP experiments can probe different surface slices and thus exhibit different compression responses which may be resolved by distinguishing bulk and surface incompressibility K_A^{vol} and K_A^{sur} . Certainly these discrepancies call for more accurate measurements and analysis of the GMR.

IV. CONCLUSIONS

The giant monopole resonance (GMR) was explored in $^{100-132}\text{Sn}$, ^{144}Sm , and ^{208}Pb in the framework of the Skyrme random-phase-approximation (RPA) with different Skyrme forces and pairing options. The calculations confirmed results of numerous previous studies [1] that GMR in ^{208}Pb (^{144}Sm) and Sn isotopes cannot be simultaneously described with one and the same Skyrme parametrization. The analysis calls for more accurate experiments and matching the TAMU and RCNP experimental data.

Dependence of GMR peak energies on the nuclear matter variables (incompressibility K , isoscalar effective mass m_0^*/m , isovector enhancement factor κ , and symmetry energy a_{sym}) was examined in $^{100,120,132}\text{Sn}$. The calculations confirmed the well-known strong dependence of the results on K . Besides, a sensitivity to the isoscalar effective mass m_0^*/m was revealed. The latter opens an additional window for further arrangement of the problem of the simultaneous GMR description in Sm/Pb and Sn nuclei. Some possible next steps in solution of this problem (further experimental progress, proper treatment of the ratio between the volume and surface incompressibility in finite nuclei, etc) were briefly discussed.

Acknowledgments

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